Mars Sample Return Earth Entry Vehicle Design: Can the Reliability Requirement be met by Emerging New Technologies?

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Planetary missions to Mars and Other Icy worlds such as Enceladus, Europa and Titan have the burden of not contaminating the planetary environment in the course of exploration (1). Missions that collect and bring back samples from these destinations have added requirement of accidental release of the samples into earth atmosphere. Planetary protection from forward and backward contaminations impose stringent reliability requirements on sample return missions especially on the design of the earth entry system and in the engineering of it. This proposed presentation will review past efforts and assess what emerging technologies could be used to address the reliability requirements.

Between 1997 and 2002, NASA working in partnership with CNES performed an end-to-end mission design study including earth entry phase. Probabilistic risk analysis was performed to lay the foundation for establishing a basis for the design elements to meet the overall planetary protection requirement (Ref 2, 3). Efforts such as chute-less entry capsule that are designed to withstand direct impact were focused on improving the reliability of the overall mission by making the entry segment entirely passive (4).

" As has been indicated by the National Academy of Sciences for scientific reasons, the possibility that the samples might be harmful, therefore, all the elements of the mission architecture must assure containment of the samples from the time of their acquisition through final disposition. The probability of containment not being assured (CNA) is 1.0E-06," from ref (2). The study performed in 2002 and reported out in 2004 looked at direct entry using an earth entry vehicle (EEV) and a Shuttle transfer system where the sample will be brought down to earth using Shuttle. Since Space Shuttle program no longer exists, the feasible options are direct earth entry vehicle or using Orion capsule instead of the Space Shuttle orbiter. For this proposed presentation, we will focus on the former and specifically the EEV.

Table 1 and Figure 1 (included at the end) are taken from Ref. 2 and they illustrate why EDL Segment needs to be robust. Earth targeted Cruise mission phase and earth targeting are two important mission segments have the two largest contributions (54% and 15%) and there are many ways to achieve the required reliability. The next biggest contributor is the entry segment (7.6%) and the remaining EDL segments are not far behind including the post impact or recovery segment. The focus of this presentation is to both assess the state of the art entry system and erroneous assumptions made in the past studies and address options that may become available to design and demonstrate the entry system that could possibly meet the stringent requirement of CAN not higher than 2.6E-07 for the entry system.

In the (1997 – 2002) study, the heritage Carbon Phenolic (CP) material, utilized on Pioneer Venus and Galileo, was baselined as the ablative thermal protection material. The EEV was a direct impact, parachute-less design as shown in Figure 2.

The heat-shield material that was baselined for the MSR-EEV was heritage Carbon-Phenolic (HCP). The heuristic argument that led to the selection of the heat-shield material HCP are problematic due to the assumptions made and also the manufacturing of HCP has atrophied. The argument for baselining HCP went some thing like this. "Given that the Venus and Jupiter entry environments are much more severe than the Sample Return Environments and the large amount of flight data for non-civilian uses it has been assumed that one can demonstrate that a CP system can meet the reliability requirements."

However HCP has its own challenges and risks associated with it. A HCP heat-shield consists of two versions of CP, one of which has not been manufactured for entry missions since Galileo and the flight heritage of that material is much more limited to just two missions (Galileo and Pioneer-Venus) or 5 probes. Given that there are two version of HCP to make one heat-shield, it requires the heatshield to have a seam between the two components which introduces additional verification challenges. HCP is also susceptible to inherent failure modes due to its 2D laminated structure.

Recent SMD and STMD funded activities have looked at the use of 3D Weaving to develop TPS materials with material architectures that are inherently more robust than 2D systems and also they are not simply one material but a family of materials. In 2012 and 2013, under the 3-D Woven TPS project, a family of materials, single and multi-layer materials were woven, some resin infused and others were not, and these materials were arc jet tested to understand the performance limit and failure modes. The family of ablative TPS materials manufactured and tested are shown in Figure 3 and also shown on this figure are three heritage materials, namely Carbon-Phenolic, Avcoat and PICA.

Recent work under the Heat-shield for Extreme Entry Environment Technology (HEEET) project have demonstrated acreage materials that are robust to entry environments of 5000+ W/cm^2 and above 5 atm. pressure, well in excess of that for sample return missions which are around 1500 W/cm2 (margined) of peak heat-flux and under 0.4 atm of peak pressure during earth entry. In Figure 4, the thermal testing performed in comparison to a range of Venus and Saturn missions are shown. It is very exciting to note that the 3-D Woven, acreage material selected for Venus and Saturn missions under the HEEET project has not shown any type of failure at any of these test points.

Knowledge gained during the HEEET project has provided insights into the complexities associated with weaving, resin infusion and other steps involved in making a robust heat-shield.

This proposed presentation will discuss in detail the challenges facing the EDL community in designing an Aero-shell that can meet the planetary protection requirements, and the opportunities 3D woven heat shield offers in terms of improved heat-shield and back-shell TPS compared to a traditional CP heatshield and some challenges that would need to be overcome to develop such a system.

References:

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2. J. Fragola, B. Putney, and J. Minarck III, "An Evaluation of Containment Assurance Risk for Earth Entry Vehicle and Space Shuttle Sample Return, Earth Entry Vehicle Office," NASA Langley Research Center Hampton, Va., September 30, 2002.
3. J. Fragola, B. Putney, and J. Minarck III, "Mars Sample Return Probabilistic Risk Assessment Final Report: An Evaluation of Containment Assurance Risk for Earth Entry Vehicle and Space Shuttle Sample Return," Contract No. 123-4119, NASA Langley Research Center, Hampton, Va.
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Table E-1. EEV Mission Phase Contribution to CAN (From Ref 2)

	5%	50%	mean	phase cont.	95%
Break-the-Chain (sample isolation)					
/MAV Launch	1.1E-10	5.4E-10	1.1E-09	0.1%	2.8E-09
Mars Orbit Rendezvous	6.7E-11	1.2E-09	6.9E-09	0.5%	1.9E-08
Mars/Earth Transit	2.6E-10	3.3E-09	3.1E-08	2.4%	1.1E-07
Earth Targeting	1.6E-07	5.0E-07	7.2E-07	54.2 %	2.0E-06
Spin Eject	7.4E-11	3.5E-10	6.2E-10	0.0%	2.1E-09
Earth Targeted Cruise	7.5E-09	8.9E-08	2.0E-07	15.1%	1.3E-06
Entry (Thermal)	2.8E-09	2.5E-08	1.0E-07	7.6%	2.6E-07
Descent (Structural)	1.0E-08	5.5E-08	8.8E-08	6.7%	3.0E-07
Impact	7.3E-09	3.5E-08	7.5E-08	5.7%	2.3E-07
After Impact	2.5E-09	2.5E-08	1.0E-07	7.6%	3.1E-07
Residual (unclassified)	2.9E-10	7.1E-10	4.4E-10	0.0%	2.1E-09
Total	**4.6E-07**	**1.0E-06**	**1.3E-06**		**2.7E-06**

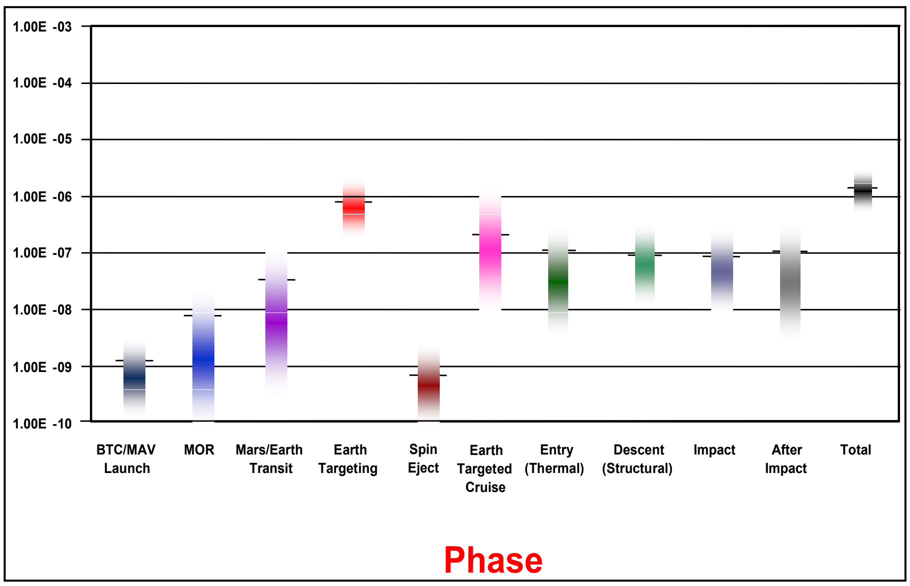

Figure 1. EEV MSR PRA Scenario Results by Phase (Taken from Ref 2)

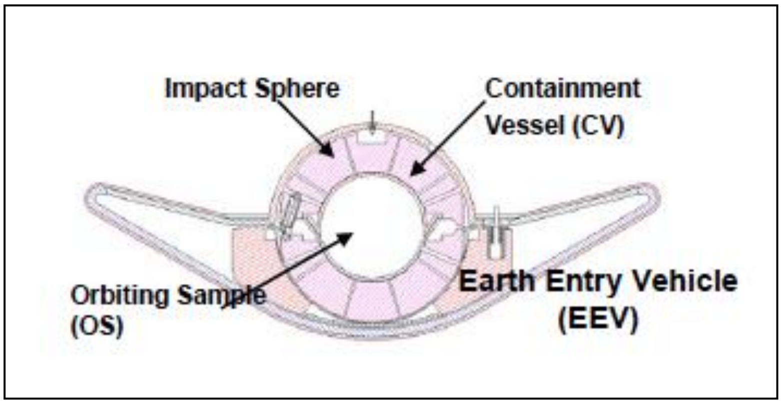

Figure 2. Mars Sample Return Earth Entry Vehicle

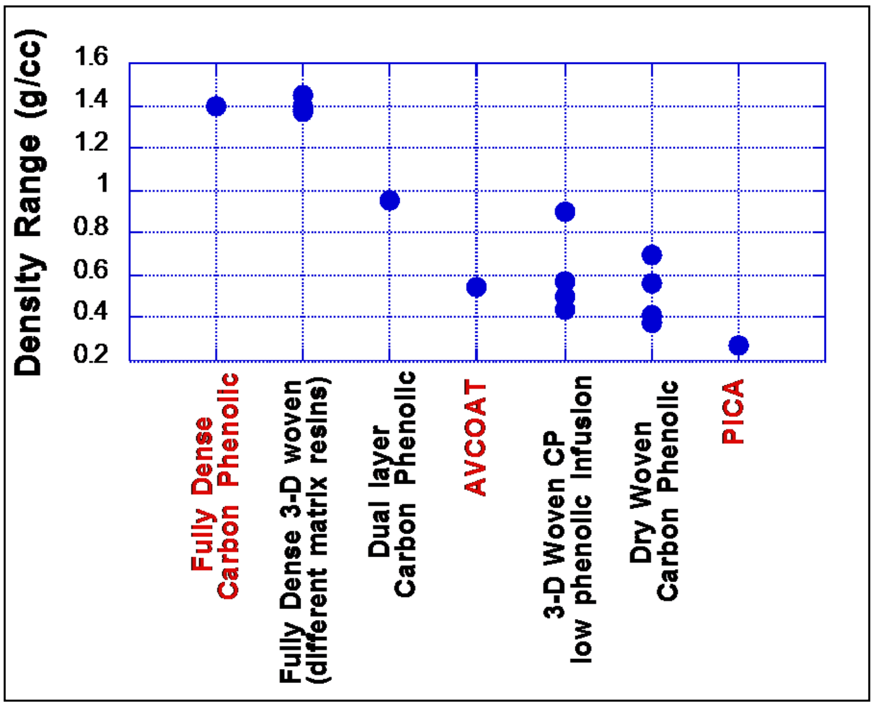

Figure 3. 3-dimensionally woven, single and multi-layer, ablative TPS materials manufactured and tested in (2012-2013). Density of the family of materials are compared with heritage ablative TPS (HCP, AVCOAT, PICA).

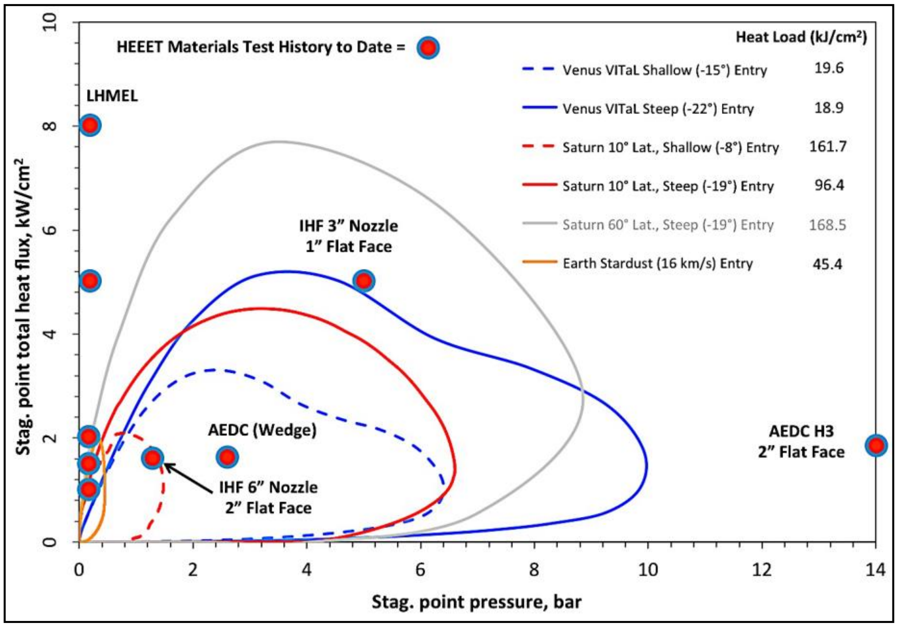

Figure 4. Thermal test conditions the HEEET material has been tested at in comparison to the mission profile in terms of heat-flux and pressure. One test was conducted at 2000 W/cm2 and at 14 atm. stagnation pressure. Another test was conducted at 8000 W/cm2 at the LHEML laser test facility with no flow. The HEEET acreage material not only survived these extreme conditions, post-test inspection showed no failure modes. In comparison, heritage CP showed anticipated failures such as spallation and ply separation